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Power Density, Field Intensity, and Carrier Frequency Determinants of RF-Energy-Induced Calcium-Ion Efflux from Brain Tissue

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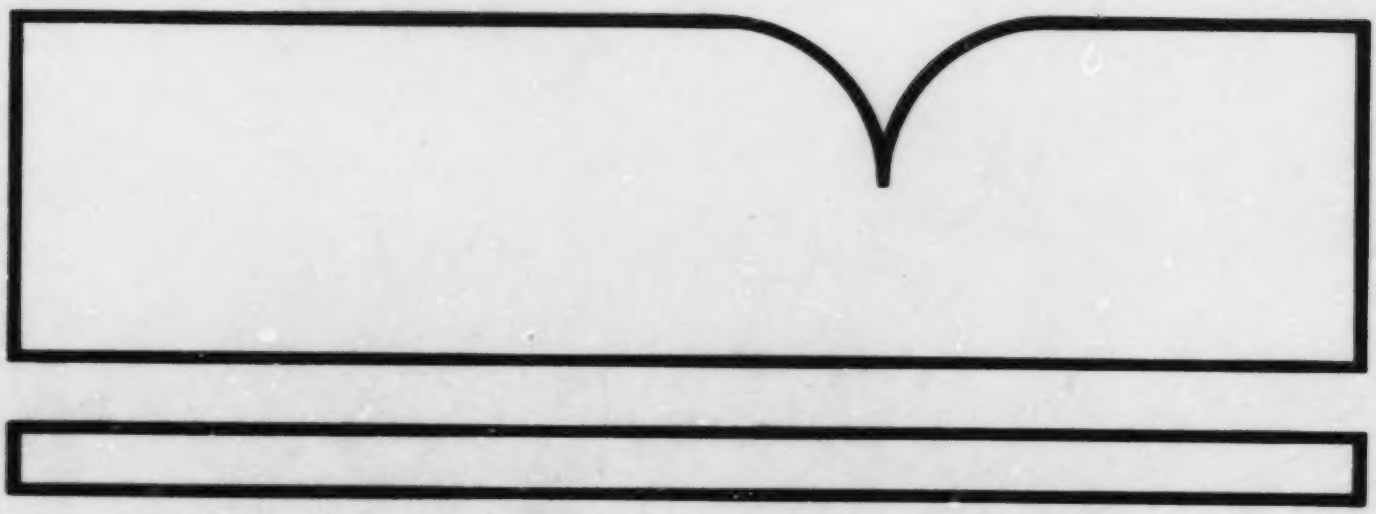

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Power Density, Field Intensity, and Carrier Frequency Determinants of RF-Energy-Induced Calcium-Ion Efflux From Brain Tissue

William T. Joines and Carl F. Blackman

Experimental Biology Division, Health Effects Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina

To explain a carrier frequency dependence reported for radiofrequency (RF)-induced calcium-ion efflux from brain tissue, a chick-brain hemisphere bathed in buffer solution is modeled as a sphere within the uniform field of the incident electromagnetic wave. Calculations on a spherical model show that the average electric-field intensity within the sample remains the same at different carrier frequencies if the incident power density (P_i) is adjusted by an amount that compensates for the change in complex permittivity (ϵ_r^*) and the change of wavelength, as a function of carrier frequency. The resulting formula for transforming P_i is seen to follow the pattern of both positive and negative demonstrations of calcium-ion efflux that have been observed at carrier frequencies of 50, 147, and 450 MHz. Indeed, all results obtained at these three frequencies, when related by P_i's that produce the same average electric-field intensity within the sample, are seen to be in agreement; no prediction is contradicted by an experiment.

Key words: calcium ions, brain tissue, radiofrequency (RF) radiation, complex permittivity (ϵ_r^*), 50 MHz, 147 MHz, 450 MHz

INTRODUCTION

Irradiation by radiofrequency (RF) fields, amplitude modulated at 6–20 Hz, has been shown to enhance the release of calcium ions from brain tissue [Adey, 1980; Blackman et al 1979]. Experiments based on a 147-MHz carrier wave indicate that the efflux of calcium reaches a maximum when the modulation is 16 Hz [Bawin et al, 1978; Blackman et al, 1979]. Additional experiments have also been conducted using 50 and 450 MHz carrier waves modulated at 16 Hz [Bawin et al, 1978; Blackman et al, 1979, 1980, 1980a,b]. This study compares all available calcium-efflux data that are based on 16-Hz modulated carrier waves of 50, 147, and 450 MHz. The reported changes in calcium-ion binding to brain tissue which are due to 16-Hz modulated RF irradiation at 50 [Blackman et al,

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Dr. Joines is also with the Electrical Engineering Department of Duke University, Durham, North Carolina.

Address reprint requests to Dr. William T. Joines, Experimental Biology Division (MD-72), Health Effects Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711.

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1980b], 147 [Blackman et al, 1979], and 450 MHz [Bawin et al, 1978] occur at different values of incident power density (P_i). The analysis in this paper examines the influence of carrier-wave frequency on the location of effective (efflux productive) power densities.

Taking into account the difference in complex permittivity (ϵ_r^*) of brain tissue at 50, 147, and 450 MHz, the P_i required to produce the same average electric-field intensity within a brain tissue sample is calculated at each frequency. The P_i's calculated in this way are translated between carrier frequencies and compared with the pattern of effective and ineffective power densities that has been observed in calcium-ion efflux experiments.

MATERIALS AND METHODS

Sample Dimensions and Spacing

In calcium-ion efflux experiments conducted by Blackman et al [1979, 1980a, 1980b], with 16-Hz modulated carriers of 50 and 147 MHz, test tubes holding the samples were placed in a polycarbonate rack within an air-filled, 50-ohm stripline. A cross-sectional view of the stripline has been published [Blackman et al, 1980a]. Four test tubes contain brain tissues plus buffer solution. The six remaining test tubes each contain buffer solution alone, of volume equal to the combined solution plus tissue volume. The spacing between sample centers is d = 1.90 cm, and the hemispherical bottom of a test tube has an inner radius, a = 0.71 cm. A spherical volume corresponding to this radius is $(4\pi/3)a^3$ or 1.5 cm^3. Each test-tube sample contained approximately this volume. A chick-brain hemisphere at the bottom of a test tube has a mean horizontal diameter of 1.0 cm and a mean height of 0.81 cm. The mean height from the top of a hemisphere to the surface of the buffer solution is 0.235 cm. The diameter of the plastic test tube is 1.42 cm, and the surface of the buffer solution is essentially flat across the entire diameter.

Equivalent P_i's Calculated at Different Frequencies

The approximately spherical test-tube samples are irradiated by a uniform plane-wave field similar to the far-field of an antenna. Hence, the vector electric-field intensity **E** induced inside a single sphere of a radius, $a \ll \lambda$ (wavelength, in air), neglecting the influence of adjacent spheres, is given by [Spiegel, 1976; Lin et al, 1973]:

$$\mathbf{E} = \frac{3\hat{z}E_0}{2 + \epsilon_r^*} - j\frac{\pi}{\lambda}(y\hat{z} - z\hat{y})\,E_0 \qquad (1)$$

where $\hat{y}$ and $\hat{z}$ are unit vectors in the y and z directions, respectively, $e_r^* = (\epsilon/\epsilon_0) - j\,(\sigma/\omega\epsilon_0)$ is the relative complex permittivity, σ is sample conductivity, ω is radian frequency, and $e^{j\omega t}$ time dependence is assumed for all fields. The first term in (1) is due to the uniform incident electric field (E_0), and the second term is due to the uniform incident magnetic field ($H_0 = E_0/\eta_0$) in the stripline, where η_0 = 377 ohms, the intrinsic impedance of free space.

In (1), since ϵ_r^* and λ change with frequency, if E_0 is changed with frequency by an amount which offsets the change in ϵ_r^* and λ, then **E** internal to the samples is kept the same at different carrier-wave frequencies. It is convenient to relate E_0 to the time-averaged P_i of radiation incident upon the sample within the stripline as

$$P_i = E_0^2/2\eta_0\ . \qquad (2)$$

Integrating the squared magnitude of (1) over a spherical volume of radius a and dividing by $4\pi a^3/3$ yields the average value of $|\mathbf{E}|^2$ as

$$|\mathbf{E}|_{av}^2 = \left|\frac{3}{2+\epsilon_r^*}\right|^2 E_0^2 + 0.1\left(\frac{2\pi a}{\lambda}\right)^2 E_0^2 . \tag{3}$$

Substituting (3) into (2) yields

$$P_i = \frac{|\mathbf{E}|_{av}^2}{2\eta_0\left[\left|\frac{3}{2+\epsilon_r^*}\right|^2 + 0.1\left(\frac{2\pi a}{\lambda}\right)^2\right]} . \tag{4}$$

From (4), $|\mathbf{E}|_{av}$ is kept the same at two different frequencies, denoted by subscripts α and β, if the incident powers are related by

$$P_{i\beta} = \frac{\left[\left|\frac{3}{2+\epsilon_r^*}\right|^2 + 0.1\left(\frac{2\pi a}{\lambda}\right)^2\right]_\alpha}{\left[\left|\frac{3}{2+\epsilon_r^*}\right|^2 + 0.1\left(\frac{2\pi a}{\lambda}\right)^2\right]_\beta} P_{i\alpha} . \tag{5}$$

Hence, to make $|\mathbf{E}|_{av}$ the same within a spherical sample of brain tissue in buffer of radius a = 0.71 cm at 50 and 147 MHz requires

$$P_{i50} = 4.46\, P_{i147} \tag{6}$$

where $\epsilon_r^* = 100 - j175$ at 50 MHz, and $\epsilon_r^* = 66 - j69.2$ at 147 MHz [Foster et al, 1979] have been used in (5).

The precise sample size and irradiation conditions used in the calcium-ion efflux experiments at 450 MHz have not been reported. For the comparison made herein, we will assume that sample sizes and irradiation conditions were similar to the ones used by Blackman et al [1979, 1980a,b] in 50 and 147 MHz experiments. Brain tissue at 450 MHz has $\epsilon_r^* = 49 - j30$ [Foster et al, 1979], and from (5) we calculate

$$P_{i147} = 3.00\, P_{i450} \tag{7}$$

to make $|\mathbf{E}|_{av}$ the same within a spherical sample of radius a = 0.71 cm at 147 and 450 MHz.

Variations from the idealized case of isolated spheres do not appreciably affect the results expressed in (6) and (7). Adjacent spheres (as for ten samples within the stripline) change E of a given sample [Joines et al, 1980]. However, the amount of change is about the same at 50, 147, and 450 MHz so that the P_i relationships in (6) and (7) are also valid for interacting samples, even though the calculations were made for an isolated sample.

RESULTS

Specific values of P_i that have been used in previously reported experiments on calcium-ion efflux from chick-brain halves are listed in Figure 1 under the carrier-wave frequency used in the experiment [Blackman et al, 1980a, b; Adey, 1980]. Values of P_i yielding significant enhancement of calcium-ion efflux (positive result) are bracketed by solid bars, and cross-hatched bars bracket the values yielding insignificant differences in efflux (negative result). No brackets indicate untested values of P_i that are predicted to yield positive or negative results. The P_i values in each horizontal row of Figure 1 are related

by equations 6 and 7. For example, 3.64 mW/cm^2 at 50 MHz, 0.83 mW/cm^2 at 147 MHz, and 0.28 mW/cm^2 at 450 MHz all produce the same average electric-field intensity within a spherical sample of brain tissue in buffer. As indicated in Figure 1, positive results have been obtained for 3.64 mW/cm^2 at 50 MHz and 0.83 mW/cm^2 at 147 MHz, while 0.28 mW/cm^2 at 450 MHz has not been tested.

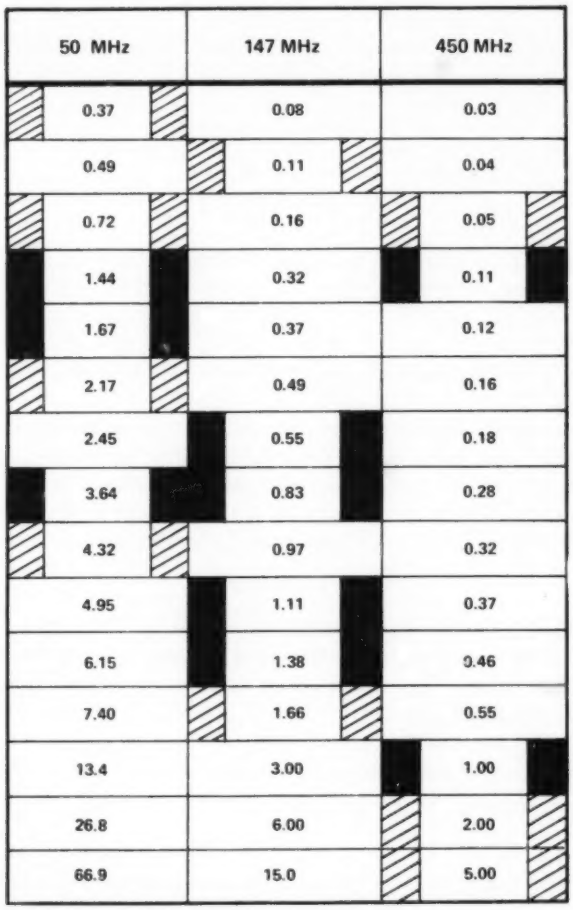

Fig. 1. Values of incident power density (P_i) which have been used in previously reported experiments on calcium-ion efflux from chick-brain halves at carrier-wave frequencies of 50, 147, and 450 MHz. Values of P_i yielding significant results are bracketed by solid bars, cross-hatched bars bracket insignificant results, and untested values of P_i are not bracketed. Note: The 50 MHz results are from Blackman et al, 1980b, the 147 MHz results are from Blackman et al, 1980a, and the 450 MHz results are from Adey, 1980.

CONCLUSION

Keeping |E| the same within a spherical model of chick brain in buffer solution at different incident carrier-wave frequencies requires that P_i be changed with frequency to compensate for the change in ϵ_r^* and λ with frequency. The resulting formulas, (6) and (7), for relating corresponding values of P_i at carrier frequencies of 50, 147, and 450 MHz are seen to render agreement among all experiments conducted so far at the three carrier frequencies.

As shown in Figure 1, there are not enough data to compare the results of calcium-ion efflux studies at many corresponding values of P_i at the three carrier frequencies. However, the negative results for 0.72, 0.11, and 0.05 mW/cm^2 at 50, 147, and 450 MHz, respectively; the positive results for 1.44 and 0.11 mW/cm^2 at 50 and 450 MHz, respectively; and the positive results for 3.64 and 0.83 mW/cm^2 at 50 and 147 MHz, respectively, support the predictions of the theoretical analysis. Further support for the theory is the fact that no result is contradicted by a corresponding experiment at a different carrier frequency. A more complete test of the theory will be obtained when additional experiments are conducted at the untested values of P_i in Figure 1.

Note: Recent studies at 147 MHz have shown a negative response at 0.49 mW/cm^2 ($P = 0.353$), and a positive enhancement at 0.37 mW/cm^2 ($P = 0.020$) in agreement with the predicted outcome.

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